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Simulation and Analysis of Crashworthiness of Fuel Tank for Helicopters

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Abstract

Crashworthiness requirement of fuel tanks is one of the important requirements in helicopter designs. The relations among the protection frame, textile layer and rubber layer of the fuel tank are introduced. Two appropriate FE models are established, one is for an uncovered helicopter fuel tank without protection frame, and the other is for fuel tank with protection frame. The dynamic responses of the two types of fuel tanks impinging on the ground with velocities of 17.3 m/s are numerically simulated for the purpose of analyzing energy-absorbing capabilities of the textile layer and protection frame. The feasibility of the current crashworthiness design of the fuel tank is examined though comparing the dynamic response behaviors of the two fuel tanks.

Keywords: fuel tank; crashworthiness; helicopter; FEM

Helicopters have been developing fast owning to their capabilities of accomplishing a great variety of tasks and adaptability to various kinds of complicated topographies. Along with the extensive applications of helicopters, the safety of pilots and passengers has become one of the most-concerned issues.

Passenger's safety is now an essential requirement in civil aircraft design. Since 1970s, the crashworthiness criterions have been established for both military and civil helicopters to improve the post-impact survivability of pilots and passengers. In conjunction with weight, load factor and fatigue life, crashworthiness (crash survival) is also considered as one of the pivotal factors during design phases in USA and most of the European countries. In recent years, crashworthiness requirement has been introduced into the design of helicopters in China[1-5].

According to the reports[1], the injuries and deaths of occupants were mainly caused by impacts and crash fires (If the fuel system was broken, the fuel would leak and contact with air and cause fire), as well as caused by toxic smoke induced suffocation and high temperature induced severe skin burn. Thus the crashworthiness design for fuel tanks is the most essential issue in the crashworthiness design for helicopters.

Fuel tanks are usually required to be located in the areas far from the passenger occupied areas or where the fuel tank is prone to be ruptured or perforated due to the large deformation of the nearby structures. The joints between the supports and the tank should be strong enough to prevent them from detaching. Fuel tanks should be made of fire-resistant and energy-absorbing materials with good ductility and long-range plastic deformation. These kinds of materials can guarantee that only large de-

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large deformations occur in the fuel tank other than being torn under the specified survivable crash conditions.

Nowadays drop tests are the main approach to assess the behaviors of helicopter crash-resistant fuel tanks[1-2]. In the test, the tank drops freely from a certain height, and then strikes onto the rigid ground, and the damage situation of the tank can be observed. For instance, according to the U.S. military standard, the tank filled with water is dropped from a height of 65 feet and the integrity of the fuel tank should be maintained with no leakage when it strikes onto the rigid ground. The drop tests offer useful guidelines for designing the crash-resistant fuel tanks. Generally, the stress conditions of the fuel tank are influenced by the tank material, arrangements of the supports, capacities and geometries of the tank. Thus, it is hard to describe the influence of an individual factor on the stress distributions of the tank. The only way of investigating the stress conditions of the tank is to conduct some drop tests of tanks with various structure arrangements and geometries. Then the critical factors could be found by statistically analyzing the test data. However, the cost of tests has always been so enormous that may be unacceptable. Therefore, estimating the detail deformation modes and evaluating its energy-absorbing capacity completely based on the drop tank test is not practical. In view of this situation, the crashing process of the fuel tank with an accessory panel is simulated in this paper by CAD, CAE, and FEM. The dynamic response behavior based on fluid-solid coupling model and the crash-worthiness parameters that play important roles in the failure of the tank are evaluated. Through analysis and comparison, it is shown that reasonably selecting tank material and protection frame to maximize its energy absorption capability is important. The results are useful for the actual crash-resistant fuel tank design.

1 Modeling Methodology

Based on the theory of nonlinear large-deformation fluid-solid coupling impact dynamics, the large-deformations, stresses and strains of the structure are simulated by the Lagrangian formulation-based FEM. Material flow is described by the Eulerian formulation-based FVM. Furthermore, utilizing the compound FEM-FVM technique, the interaction between the structure and fluid is simulated through analyzing the fluid-structure coupling at the fluid-solid boundaries. The differential equation of motion for explicit/implicit time integration FEM is

$$\boldsymbol{M}\ddot{U} + \boldsymbol{C}\dot{U} + \boldsymbol{K}U = \boldsymbol{F}(t) \tag{1}$$

where $\boldsymbol{M}$ is the mass matrix, $\boldsymbol{C}$ is the damping matrix, $\boldsymbol{K}$ is the stiffness matrix, $\boldsymbol{F}$ is the generalized external excitation force.

Use FVM to conduct the volume integral over a volume enveloped by an arbitrary closed surface, and the integral governing equations are obtained as follows:

Conservation of mass:

$$\frac{\partial}{\partial t}\iiint \rho \mathrm{d}V = -\iint \rho u \mathrm{d}S \tag{2}$$

Conservation of momentum:

$$\frac{\partial}{\partial t}\iiint \rho u \mathrm{d}V = -\iint \rho u u \mathrm{d}S + \iint T \mathrm{d}S \tag{3}$$

Conservation of energy:

$$\frac{\partial}{\partial t}\iiint \rho e_{\mathrm{t}} \mathrm{d}V = -\iint \rho e_{\mathrm{t}} u \mathrm{d}S + \iint uT \mathrm{d}S \tag{4}$$

Equation of state:

$$P = f(\rho, e_{\mathrm{t}}) \tag{5}$$

where u is the mass flow speed, ρ is the mass density, e_{t} is the energy, T is the applied surface traction, S is the surface around the volume V. Let each element be a closed volume and the instant shape of the element can be obtained by multiplying the time step, Δt, from time t_n to t_{n+1} where subscript n and n+1 denote successive time, then using the linear interpolation and Gauss integration the variations from t_n to t_{n+1} of the element can be obtained.

The theoretical analysis of fluid-solid interaction can be found in Taylor and others' paper[6-7], the solution of momentum transfer for one-dimensional wave pulse impinging on a solid was given by them. If the mass density and sound speed of the impinging fluid are denoted by ρ_f and c_f respectively, the thickness of plate is h, the momentum per unit area is I, then

$$\frac{I}{I_0} = 2q^{q/(1-q)} \tag{6}$$

where

$$q = \frac{t_0 \rho_f c_f}{\rho h} \tag{7}$$

$$I_0 = \int_0^\infty p \mathrm{d}t = p t_0 \tag{8}$$

$$p = p_0 \mathrm{e}^{-t/t_0} \tag{9}$$

where p_0 is the pulse peak in the free-field at any point in the field, t_0 is the decay period.

2 Simplified Model for the Tank and the Selection of Material Parameters

The uncovered fuel tank is composed of two layers, a crash-resistant textile out layer and an oil-proof rubber inside layer, as shown in Fig.1.

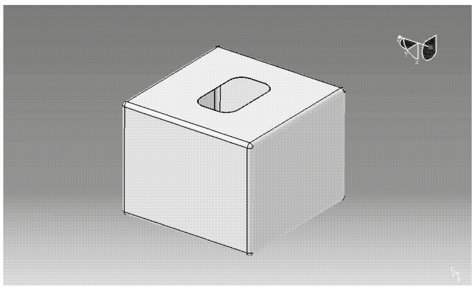

Fig.1 Geometric model of the uncovered fuel tank.

These two layers are adhesively bonded together. Accessory panel located at the bottom of the tank is made of hard aluminum. Fig.2 shows the fuel tank with a protection frame. After lots of calculations, it is found that the interior rubber layer is relatively less affected during the entire crash process, and its stress peak is approximately one tenth of ultimate strength of the textile layer. Therefore, to simplify the analysis, the uncovered tank can be considered as a single textile layer to reduce the computing time.

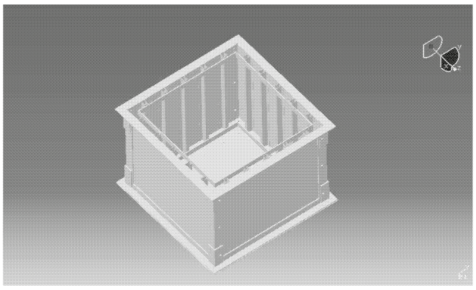

Fig.2 Geometric model of the protection frame.

Considering the anisotropy of the textile material, tension tests were performed with specimen along two orthogonal directions (longitude direction L and transverse direction W) in the Fourth Rubber Factory in Shenyang. The stress-strain curves of the textile under quasi-static loading are concluded in Fig.3 and Fig.4. According to the practical operating conditions, the strain rate effect can be reasonably ignored because the tank impinges on the ground at a rather low speed.

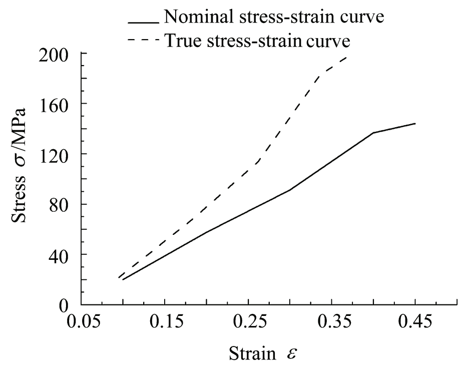

Fig.3 Material parameter curve for the longitudinal direction.

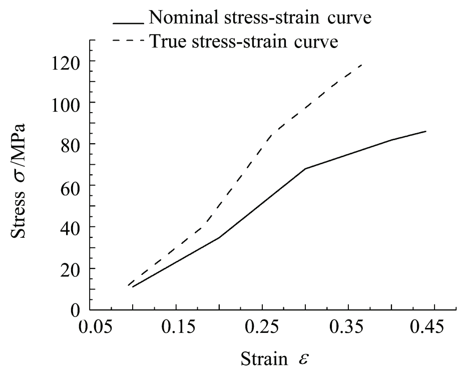

Fig.4 Material parameter curve for the transverse direction.

3 Finite Element Model for the Fuel Tank

Considering that the textile material of the tank is anisotropic, shell elements of composite materials can be employed. These types of elements can describe the anisotropy of materials. However, to use these types of elements, PCOM elements are required, and the elastic materials model are usually applied to brittle materials rather than nonlinear elastic or elastic-plastic materials. Sometimes uncontrollable hourglass mode may occur for large-deformation problems. Therefore, this model can't be applied in this paper. Another candidate is the 3D solid element, which is suitable for anisotropic elastic materials. Large deformations, large rotations and large strains are permitted. Since the span-thickness ratio of the structure exceeds 300∶1 in this study, numerical troubles will occur and it seems still inappropriate for selecting the element. Finally, the isotropic shell element is selected in this study due to the fact that this element possesses many theoretical modes such as Belytschko-Tsai, Hughes-Liu, and Key-Hoff etc. Large deformations, large rotations, large elastic-plastic strains are permitted and many failure criterions are available. The default Belytschko-Tsai shell theory is employed here.

The meshes for the uncovered tank and the tank with a protection frame are shown in Fig.5 and Fig.6, respectively. Distributions of elements for each component are shown in Table 1.

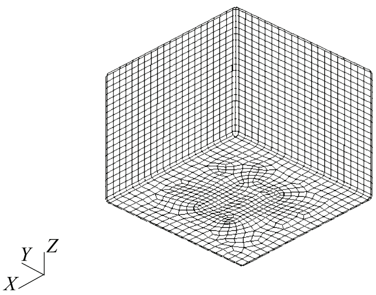

Fig.5 Finite element model for the uncovered fuel tank.

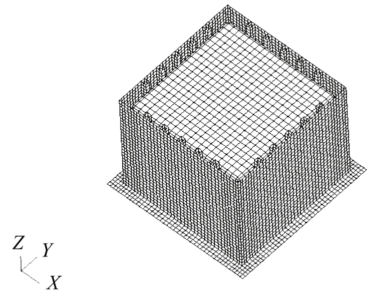

Fig.6 Finite element model for the uncovered fuel tank in the protection frame.

Table 1 Distribution of the elements for the FEM model

	Numbers of shell elements	Numbers of Euler elements	Total numbers
Fuel tank	2 858	0	2 858
Protection frame	11 386	0	11 386
Water	0	9 747	9 747
Total numbers	14 244	9 747	2 3991

4 Analysis of the Numerical Results

Two kinds of fuel tanks impinging on the ground with velocities of 17.3 m/s are numerically simulated. It may be noted that high stresses and large strains of the protection frame primarily occur in the vicinity of the central regions of the four sides. It is due to the fact that these positions are the main areas for restricting the transverse large deformation of the fuel tank. It is also observed that stress-concentrations appear in some regions such as the contact area between the top frame and side frame, the clapboard supporting section and hinge connecting section etc. But their maximum stresses are less than the ultimate strength of the material. Furthermore, there are some fillets in the actual structure, hence the protection frame will not be damaged under survivable drop conditions.

The distributions of strains and deformations of the two fuel tanks under same operating conditions at the same time are shown in Fig.7 and Fig.8, respectively. It is shown that the fuel tank with the protection frame can almost keep its original shape. The values of strains and displacements of the fuel tank with the protection frame are much lower than

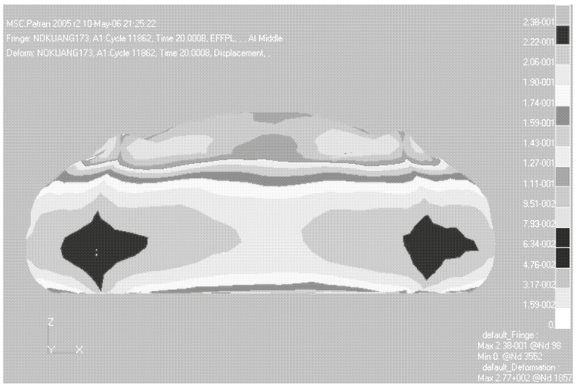

Fig.7 Distributions of the effective plastic strains of the deformed fuel tank without protection frame at the 20th millisecond.

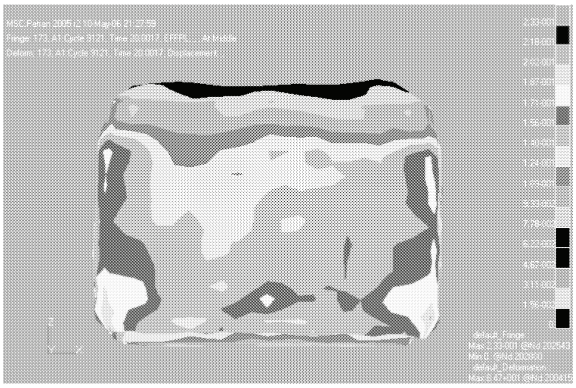

Fig.8 Distributions of the effective plastic strains of the fuel tank with the protection frame at the 20th millisecond.

those of the fuel tank without a protection frame. It is of benefit to the crashworthiness designs of fuel tanks. Because there are many oil supply lines which are not contractible inside the softening fuel tank, only when the original shape of the tank is properly maintained, it will not be punctured easily by those oil supply lines and the leakage might be prevented.

Fig.9 shows the protection frame has also played a significant role in reducing the peak stress of the fuel tank.

During dropping, it is of great interest that how the energy of the whole system is converted. There is only kinetic energy of the system just before the tank strikes the ground, as shown in Fig.10. During striking, most of the kinetic energy is converted into the inner energy of the fuel (oil), as well as the strain energy of the protection frame and the textile layer and the plastic dissipation. The total kinetic energy is then decreased and the speed of the system is declined. Then the system reaches an instantaneous force balance, part of the strain energies of the protection frame and textile material is released, the system may bounce upward. Because most of the energies are dissipated due to the plastic deformations of the protection frame and textile material, the kinetic energy of the system bouncing upward is decreased drastically and the system would be even no longer rebounding. Generally in a certain period of time, the kinetic energy of the system is totally dissipated, and then the fuel tank will be in a state of rest. The energy-absorbing capabilities of the protection frame and textile material are shown in Table 2.

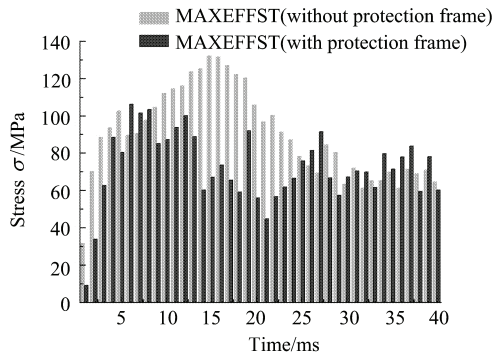

Fig.9 Comparison of maximum effective stresses.

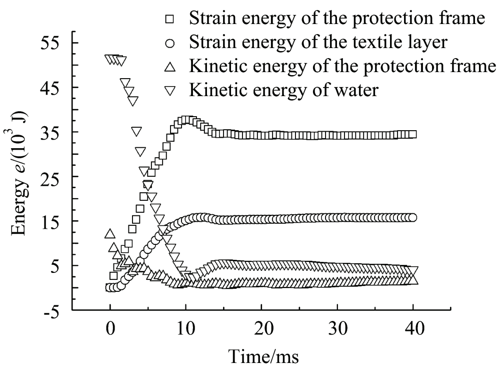

Fig.10 Energy transformation.

Table 2 Energy-absorbing capability

	Final strain energy /J	Absorption ratio /%
Protection frame	34 353	53
Textile material	15 742	24

5 Conclusions

Because of the complexity of the structure, it is difficult to obtain exact solutions for the fuel tank impact response problems. The crashworthiness of the fuel tank is evaluated based on CAD, CAE, and FEM approaches to perform a comprehensive study on the dynamic responses throughout the entire impact process. From the numerical results, it is found that the fuel tank without the protection frame undergoes large lateral deformation when impinging onto the rigid ground. This is not good for the crashworthiness of the structure. The original shape of the fuel tank with a protection frame can be remained perfectly, and the peak stress is effectively decreased. In addition, the energy dissipation in the protection frame and textile layer is discussed in detail. By comparing the kinetic energy dissipation of each structural component, it can be seen that the protection frame plays a more significant role in absorbing and dissipating energy during impact. Theses results not only explain that the protection frame is necessary for improving the crashworthiness of the fuel tank, but also help the helicopter designers develop improved crash-resistant fuel tanks.

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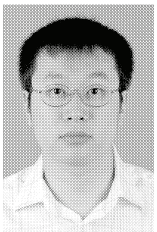
Biographies:



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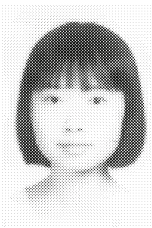

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